UNCLASSIFIED

AD NUMBER
AD528266
NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Distribution limited to U.S. Gov't. agencies only; Test and Evaluation; Dec 73. Other requests for this document must be referred to Director, Naval Research Lab., Washington, D. C. 20375.

AUTHORITY

NRL notice, 27 Dec 1995

THIS PAGE IS UNCLASSIFIED

AD NUMBER

0528 286

CLASSIFICATION CHANGES

TO

UNCLASSIFIED

FROM

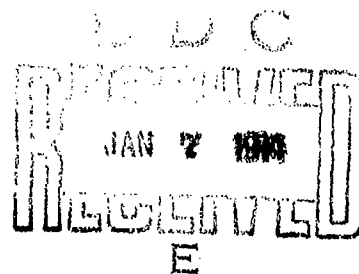CONFIDENTIAL

AUTHORITY

31 DEC 38 PER DCC MARKINGS

AD52

DOPPLER Only Navigation Using the Timation II Satellite
[Unclassified Title]

T. B. McCASKILL, C. W. ARVEY,
AND H. B. GARDNER

Space Metrology Branch
Space Systems Division

December 3, 1973

NAVAL RESEARCH LABORATORY
Washington, D.C.

NATIONAL SECURITY INFORMATION

Unauthorized Disclosure Subject to Criminal Sanctions.

CONFIDENTIAL

CONTENTS

ABSTRACT
(Confidential)

(U) The TIMATION II satellite is an experimental model which is part of a range and doppler measurement satellite system proposed by NRL as the Navy's candidate for the Department of Defense Navigation Satellite System (DNSS). The TIMATION project has been conducted at NRL under the sponsorship of the Navy Space Project Office (PME-106) and the Naval Air Systems Command. A doppler mathematical model has been devised which permits ready analysis of the doppler data collected at the CBD field station over a 1-1/2-year time period.

(C) The studies performed have shown that the best navigational accuracies, having an RMS of 53 meters (174 feet), are achieved by using dual-frequency doppler measurements. The 400-MHz single-frequency data give the next best accuracy, with an RMS of 84 meters (276 feet), and are followed by the 150-MHz single-frequency data, which yield an accuracy of 739 meters (2424 feet) RMS. The data collected are three types: 1K, 10K, and 40K doppler count. By varying the count interval, the effect of measurement time on navigational accuracy can be observed.

DOPPLER ONLY NAVIGATION USING THE TIMATION II SATELLITE

INTRODUCTION

(U) The TIMATION (Time Navigation) satellite navigation system (1,2) has been proposed for the Department of Defense Navigation Satellite System (DNSS). TIMATION has the capability of providing worldwide instantaneous and continuous three-dimensional position fixes and high-accuracy time transfer via satellite. The TIMATION project is conducted by the Naval Research Laboratory under the sponsorship of the Navy Space Project Office (PME 106) and the Naval Air Systems Command.

(U) Two passive-measurement techniques are employed by the TIMATION system. The primary measurement technique uses passive ranging, which is accomplished by measuring the time difference between the navigator's clock and the satellite clock. With the second technique, the satellite transmitter frequency's doppler shift is measured; this is accomplished by measuring the frequency difference between the navigator's frequency source and the satellite frequency standard. A position fix may then be calculated by use of (a) range measurements only (3,4,5), (b) simultaneous range-doppler measurements (6), or (c) doppler measurements with time synchronization (7) derived from ranging. This report presents an analysis of the navigation and frequency difference results using doppler measurements from the TIMATION II satellite.

THE TIMATION II SATELLITE

(U) The TIMATION II satellite (Fig. 1) is in a 500-n.-mi. near-circular orbit with an inclination of 70 degrees. This orbit results in four to six satellite passes per day that may be used for navigation. TIMATION II weighs 125 pounds and consumes an average of 18 watts of power, provided by solar cells and batteries. The satellite's antennas are kept pointed toward the earth by use of an extendable boom which gives two-axis gravity gradient stabilization. The transmitter has a high-precision quartz-crystal 5-MHz frequency standard which is kept under active temperature control (8). The frequency standard is tunable upon command by the use of an electromechanical tuning mechanism. The satellite clock is also tunable upon command via an electronic tuning technique. The satellite transmits signals which are used for navigation in two frequency bands, with carrier frequencies of 149.5 and 399.4 MHz. The 149.5- and 399.4-MHz signals are coherent with each frequency synthesized from the frequency standard. The transmitted signals may be used to obtain range and/or doppler measurements for navigation and time transfer.

DOPPLER EQUIPMENT DESCRIPTION

(U) The TIMATION range receivers at the NRL Chesapeake Bay Division (CBD) were modified to make doppler-shift measurements of the carrier frequency transmitted by the TIMATION II satellite at nominal frequencies of 149.5 and 399.4 MHz. The dual-frequency
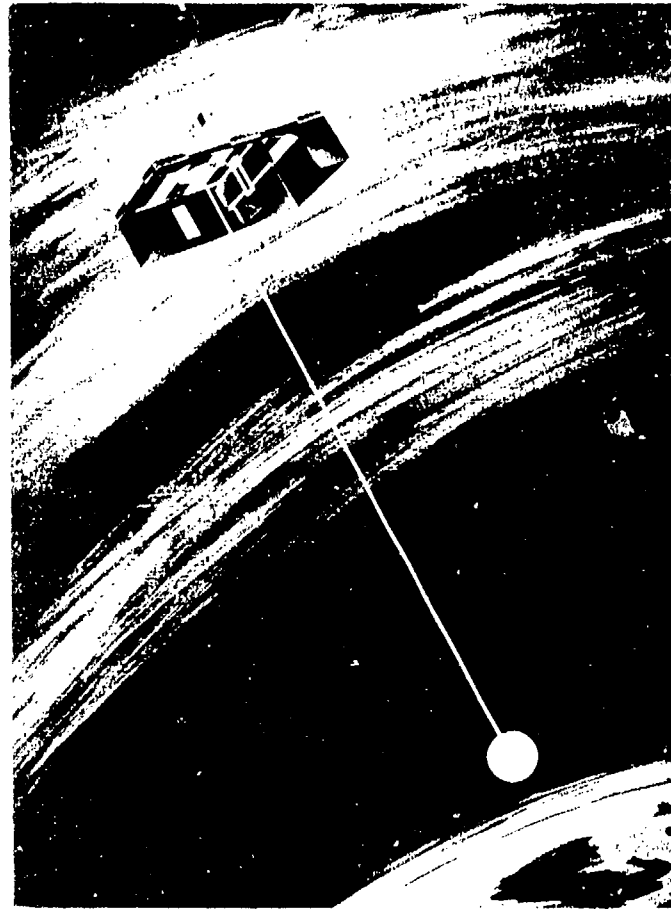
(U) Fig. 1 — The TIMATION II satellite

measurements were used to measure and eliminate first-order doppler ionospheric refraction. This procedure results in a more accurate position fix than position fixes computed using single frequency measurements. The frequency-difference measurements (Fig. 2) were obtained by measuring the time interval necessary for a counter to accumulate a fixed number of cycles of the doppler shift; this measure was then translated to the audio-frequency range. The doppler shift was biased by 20 kHz for both the 149.5- and 399.4-MHz doppler shift. This offset was used because the doppler shift changes from positive to negative as the satellite's motion relative to the observer changes from advancing to receding. The time-interval measurement was triggered by the first positive-going cycle of the doppler after the beginning of the minute and was stopped when the accumulator registered a preset number of cycles. One doppler measurement per minute was utilized to obtain a position fix. The time-interval measurement was then transferred to paper tape with a resolution of 0.1 microsecond, along with a message header which gives the station identification, satellite pass identification, and the number of cycles counted.
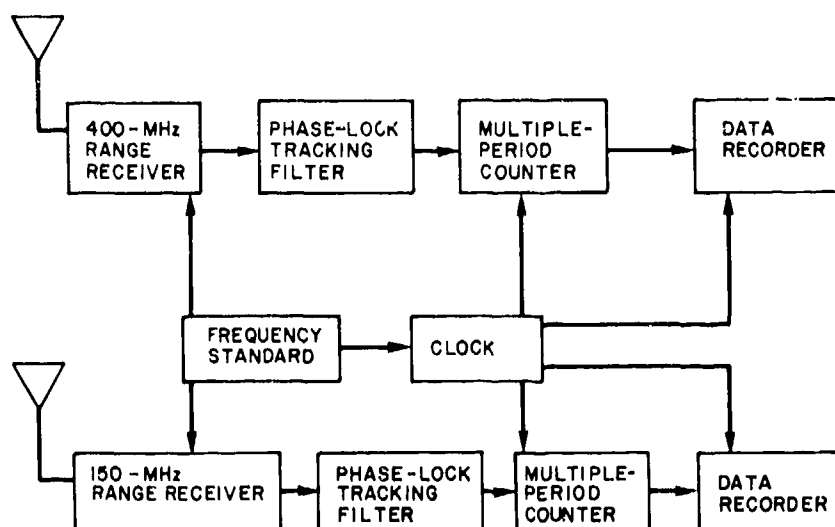
(U) Fig. 2 — TIMATION range and doppler
functional block diagram

DOPPLER MATHEMATICAL MODEL

(U) A least-squares technique (3) was utilized to obtain a solution for the navigator's
position from doppler-shift measurements. The equipment measured the integral of a
frequency difference which is convertible to an apparent doppler shift. The doppler-shift
measurements at each frequency (149.5 and 399.4 MHz) were then combined to remove
first-order doppler ionospheric refraction. Using the satellite ephemeris and an assumed
position $\bar{r}_s$ for the navigator, the doppler shift was then calculated each time a measurement
was taken. These calculated values were then used to form a set of residuals, denoted by
$(O_i - C_i)$, where O_i denotes the observed doppler shift and C_i denotes the calculated
values for the "ith" measurement. The set of residuals was then edited to remove spurious
data. This final set of residuals was used with the least-squares algorithm to solve for the
navigator's position.

(U) The model used assumes that the frequency difference between the satellite frequency
standard and the navigator's frequency source is constant during a single satellite pass.
This frequency correction is defined to be the negative of the $(O - C)$, or $K = -(O - C)$.
For an entire satellite pass, K is solved for simultaneously along with the navigator's
latitude and longitude. The algorithm used estimates five parameters for a single pass,
which are $(K, \Delta x_s, \Delta y_s, \Delta z_s, \lambda)$, where $\Delta \bar{r}_s = (\Delta x_s, \Delta y_s, \Delta z_s)$ is a correction to the
assumed position $\bar{r}_s$, and λ is a Lagrange multiplier used to constrain the solution to the
surface of the geoid.* The program also computes an RMS noise level for the frequency
measurements and a Geometrical Dilution Of Precision (GDOP) number for the position
fix. This iterative solution usually converges in two or three iterations.

*The coordinate system used is a right-handed cartesian coordinate system with z the polar axis, x along
the Greenwich meridian in the equatorial plane, and y completing the right-handed set. The observer's
coordinates with respect to this set are denoted by $\bar{r}_s = (x_s, y_s, z_s)$.

(U) The least-squares program does not estimate the navigator's velocity; hence the velocity must be known from other sources. If the navigator's horizontal velocity components are included as unknown parameters, a dilution of the entire solution results.

(U) The data collected by a fixed observer from several satellite passes may be used to obtain an improved estimate of latitude and longitude. For N satellite passes, the parameters that would be estimated are

$$(K_1, K_2, \cdots K_N, \Delta x_s, \Delta y_s, \Delta z_s, \lambda)$$

where $K_1, K_2, \cdots K_N$ refer to the frequency-difference constants for each of the satellite passes. This same information may also be used to estimate the observer's height in addition to the latitude and longitude. The solution is obtained by removing the constraint, λ, and solving for $(K_1, K_2, \cdots, K_N, \Delta x_s, \Delta y_s, \Delta z_s)$.

DOPPLER NAVIGATION RESULTS

The doppler data for this report were taken at the CBD field station covering a 1-1/2-year time span, from Sept. 9, 1971, through Mar. 27, 1973. The doppler data used are divided into three major types: 1K, 10K, and 40K doppler count. The terms 1K, 10K, and 40K refer to the number of cycles of doppler shift (1000, 10,000 or 40,000) registered by the counter when taking the time-interval measurement discussed previously in this report. A further division of the 40K doppler-count data was necessary because of equipment changes that affected the accuracy of the data. The time spans and number of satellite passes for each set of data are shown in Table 1. The time gaps in the data are present because data were collected only during periods when the satellite was in 100-percent sunlight. This restriction resulted from the fact that the batteries would charge at a rate to sustain sufficient power for operation of the transmitter only during 100-percent sunlight periods. Damage to a solar-cell panel during the launch of the satellite brought about this limitation. The accuracy of the data is not affected by these time gaps.

(U) Table 1
Classification of Data Sets

Data Set Number	Calendar Date	Data Span Days	Number of Passes	Doppler Data Type
1	11/8/71-12/16/71	49	23	1K
2	9/9/71-11/1/71	54	100	10K
3	2/8/72-10/25/72	261	266	40K
4	11/28/72-3/27/73	119	140	40K
5	1/10/73-3/27/73	77	105	40K
6	2/8/72-3/27/73	413	407	40K

(U) Two statistical measures are used in computing the accuracy of each group of passes: the circular error probable (CEP) and the root mean square (RMS). Both of these values are printed in the summary block on the navigation plots (Figs. 4, 6, 8, 10, 12, and 14) and in Table 2.

(C) Table 2
Navigation Accuracies and Frequency Noise Levels of the Data Sets

Data Set Number	Navigational Accuracy				
	CEP (m)	RMS (m)	Mean Latitude (m)	Mean Longitude (m)	RMS Frequency Noise Level (pp10 (10))
1	189	240	25	+13	±22.0
2	41	58	−11	7	±3.8
3	63	82	0	10	±4.1
4	52	64	−6	15	±2.6
5	48	53	−8	−13	±3.2
6	56	77	−2	11	±3.7

(U) The navigation plots have other features which aid in interpreting the data. One of these features is an arrow extending from each datum point which shows both the direction the satellite was traveling when it passed over the receiving station (the stem extending from the datum point), and location of the satellite east or west of the station at the satellite time of closest approach, TCA (the flange at the end of the stem). The top of the plot is to be considered north and the right side east, for purposes of reading these arrows. The latitude and longitude bias values ($\Delta \bar{r}_s$) for each set of passes (distance from the assumed position measured in meters) are also printed in the navigation-plot summary boxes. The sign convention used for the latitude and longitude bias values is + for north and east and − for south and west of the assumed position.

(U) The assumed positions used in the navigation solutions were obtained from the survey coordinates for the CBD field station. Each point on the navigation plots results from performance of a navigation solution, as discussed in the section on the mathematical model, using all the data points from a single satellite pass. Different values for assumed position are used later in this report; however, their use will be explicitly stated in the text.



(C) The 1K doppler-count data set was taken in late 1971, with a total of 23 passes in this first data set. Figure 3 shows the doppler (O − C) versus time from TCA plots for data set 1. Each (O − C) curve is computed from the assumed position (AP) of the CBD station, with the average frequency difference removed from each point. The (O − C)'s

are expressed in both units of fractional frequency (pp10(10)) and Hertz at 399.4 MHz. The relatively high noise level of $\pm 22.0 \times 10^{-10}$ present in these data (Table 2) is mainly responsible for the large RMS and CEP values for the navigated points. The navigated points in Fig. 4 exhibit a scatter with no distinct pattern, except an absence of position fixes within 50 meters of the AP.

(C) The 10K doppler count data (data set 2) were taken in the time period of September and October 1971. The (O — C)'s for the 10K data, given in Fig. 5, exhibit a considerable improvement over the 1K frequency noise, with an RMS value of $\pm 3.8 \times 10^{-10}$. The first-order-of-magnitude increase in measurement time resulted in almost one order of magnitude decrease in frequency noise. The 10K navigations (Fig. 6) exhibit an improvement from an RMS of ± 240 m for the 1K to ± 58 m for the 10K doppler. The less-than-one-order-of-magnitude improvement in navigations indicates that other factors have become significant.

(C) The 40K navigation results are divided into four partitions because of equipment changes that influenced the navigation accuracy. Data set 6 incorporates all passes taken between Feb. 8, 1972, and Mar. 27, 1973. Figure 7 shows the (O — C)'s for all 407 passes, with an RMS value of $\pm 3.7 \times 10^{-10}$, which is approximately the same as the frequency noise for the 10K doppler data. Figure 8 gives the corresponding navigations, with an RMS value of ± 77 m. Data set 3, a subset of data set 6, contains 266 passes taken between Feb. 8, 1972, and Oct. 25, 1972. Figure 9 shows the doppler (O — C)'s with a frequency RMS of $\pm 4.1 \times 10^{-10}$, which is less than the composite of 407 passes. Figure 10 presents the corresponding navigations with an RMS value of ± 82 m. Figure 11 shows the (O — C) curves for data set 4, with a frequency RMS of $\pm 2.6 \times 10^{-10}$. Figure 12 gives the corresponding navigations with an RMS of ± 64 m. Between the time period from Oct. 25, 1972, to Oct. 27, 1972, an error of one microsecond was discovered in the time-interval readout, which reduced the frequency resolution of the equipment. Before data set 5 the 400-MHz tracking filter was found to be malfunctioning and was subsequently repaired. The quality of the data thereafter was improved, as can be seen from the (O — C) and navigation curves for the set 5 data. Figure 13 represents the (O — C) curves for this last data set, which shows a frequency noise level of $\pm 3.2 \times 10^{-10}$, a slight improvement over the 10K results. Figure 14 presents the corresponding navigations with an RMS value of ± 53 m.

(U) Reference to Fig. 14 shows that the navigations are not random but are correlated with direction of satellite pass and with the location of the satellite east or west of the station at TCA. Detailed analysis of the previous navigation plots (Figs. 4, 6, 8, 10, and 12) shows a similar correlation that is masked by other factors such as measurement noise and equipment errors.
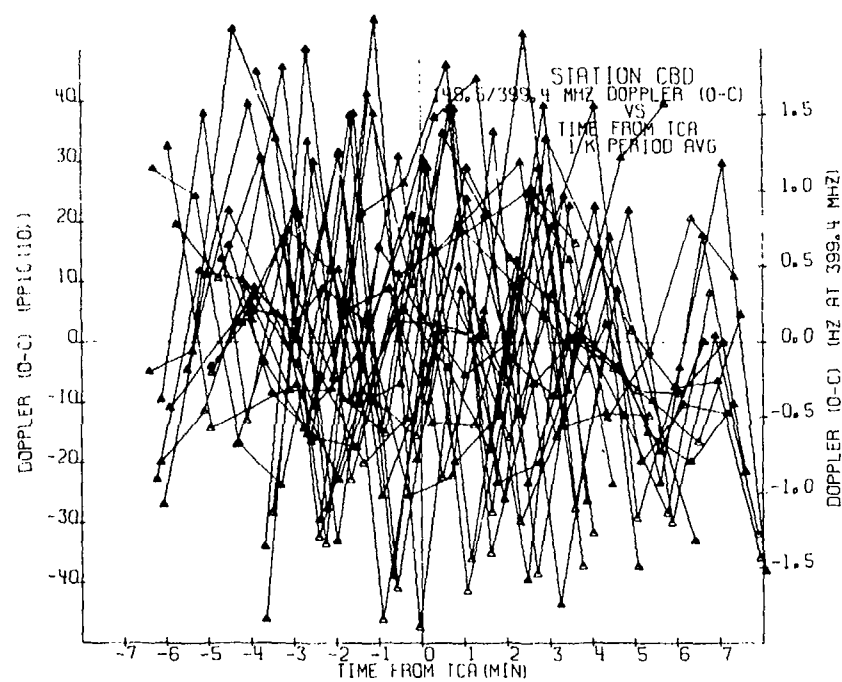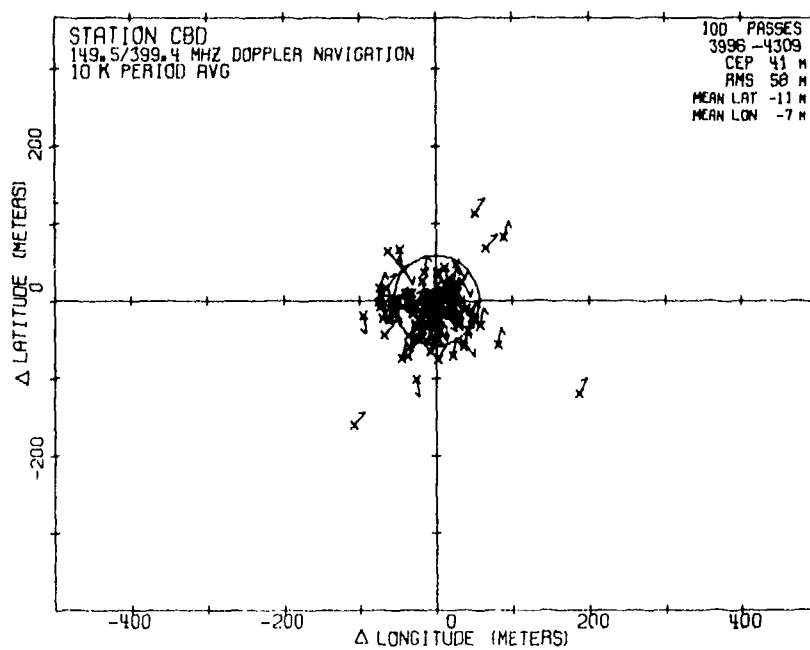
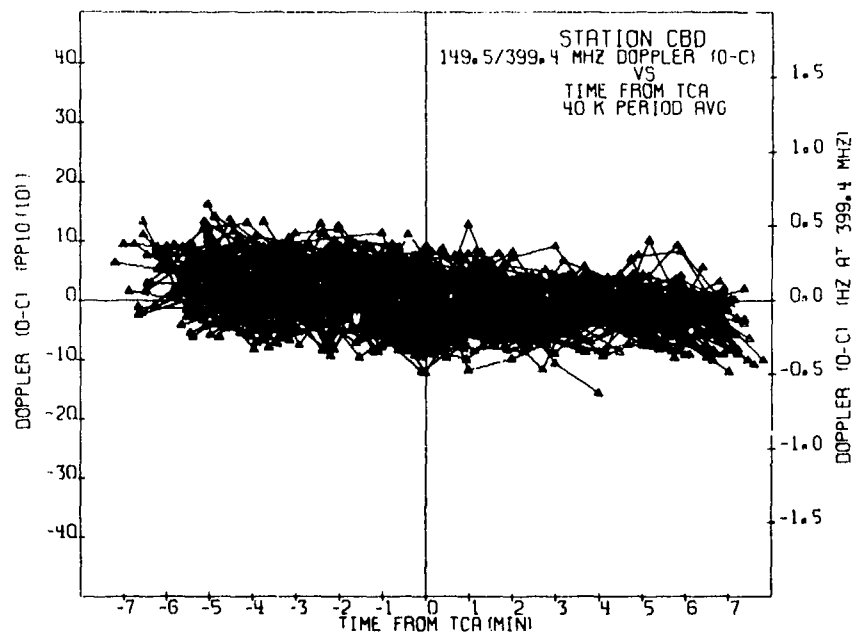(U) Fig. 3 — 1K doppler (O — C) versus time from
TCA, data set 1
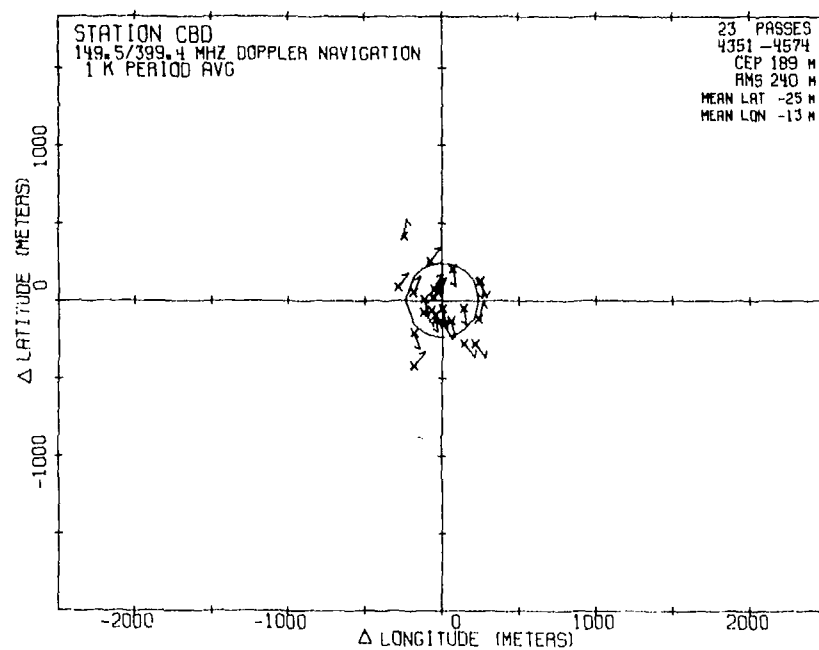
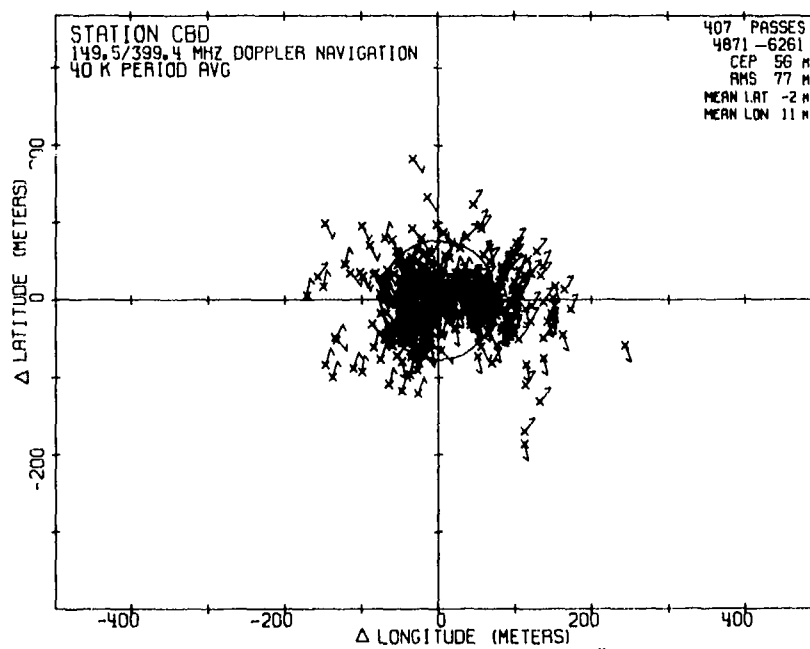(C) Fig. 4 — 1K doppler navigations

McCASKILL, ARVEY, AND GARDNER   CONFIDENTIAL
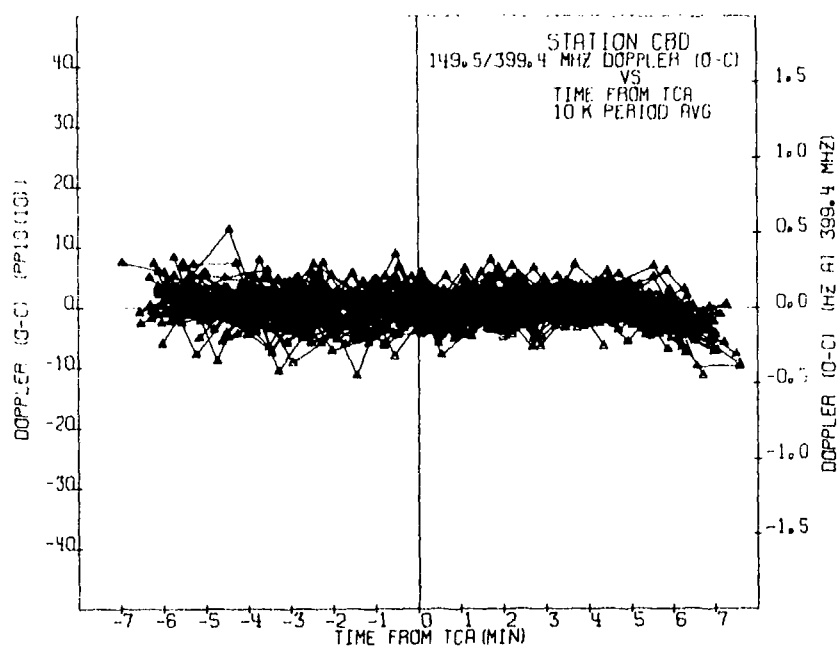
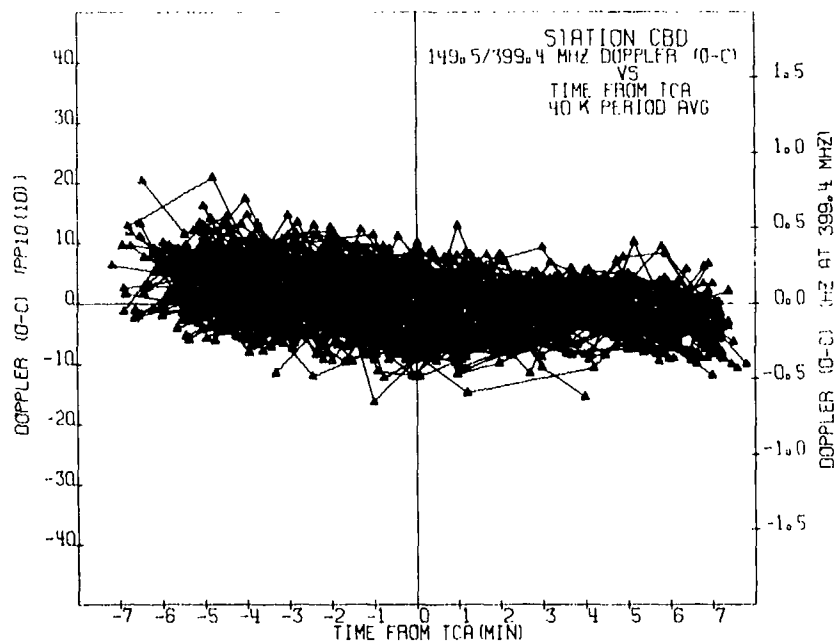(U) Fig. 5 — 10K doppler (O — C) versus time from
TCA, data set 2

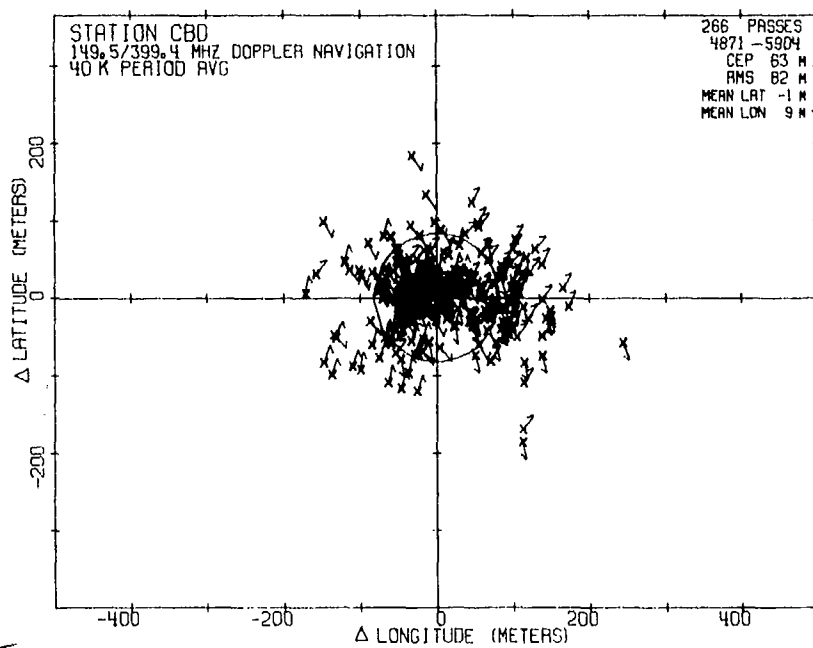(C) Fig. 6 — 10K doppler navigations

(U) Fig. 7 — 40K composite doppler (O — C) versus time
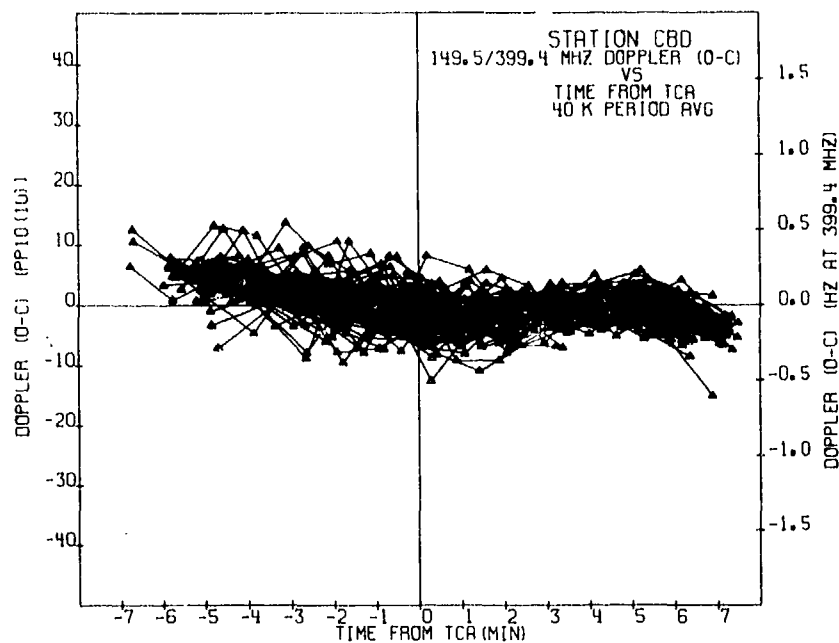from TCA, data set 6

(C) Fig. 8 — 40K composite doppler navigations, data set 6
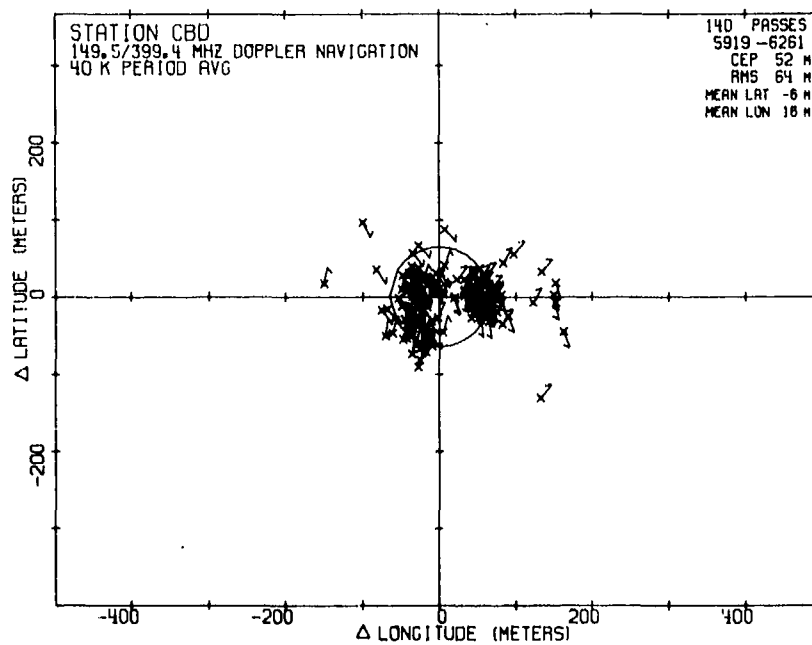
(U) Fig. 9 — 40K doppler (O — C) versus time
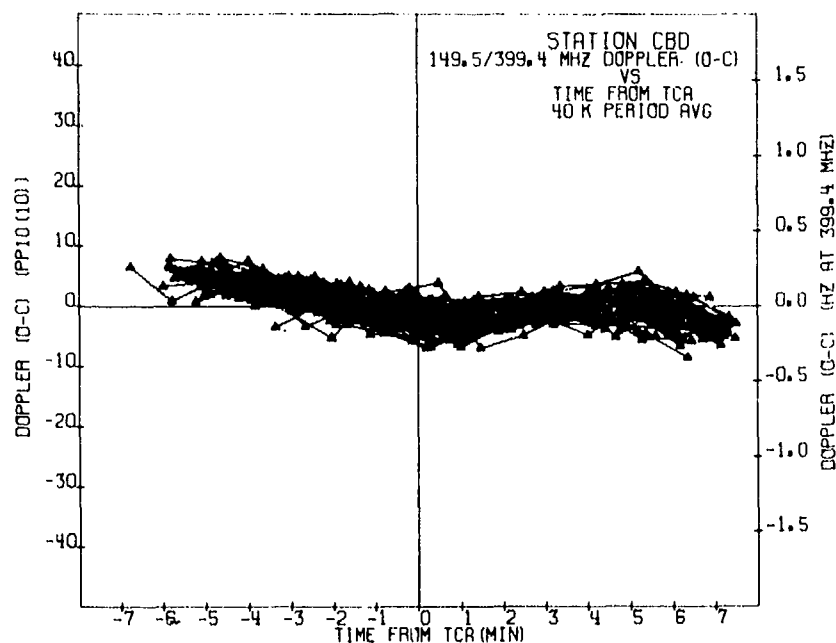from TCA, data set 3

(C) Fig. 10 — 40K doppler navigations,
data set 3
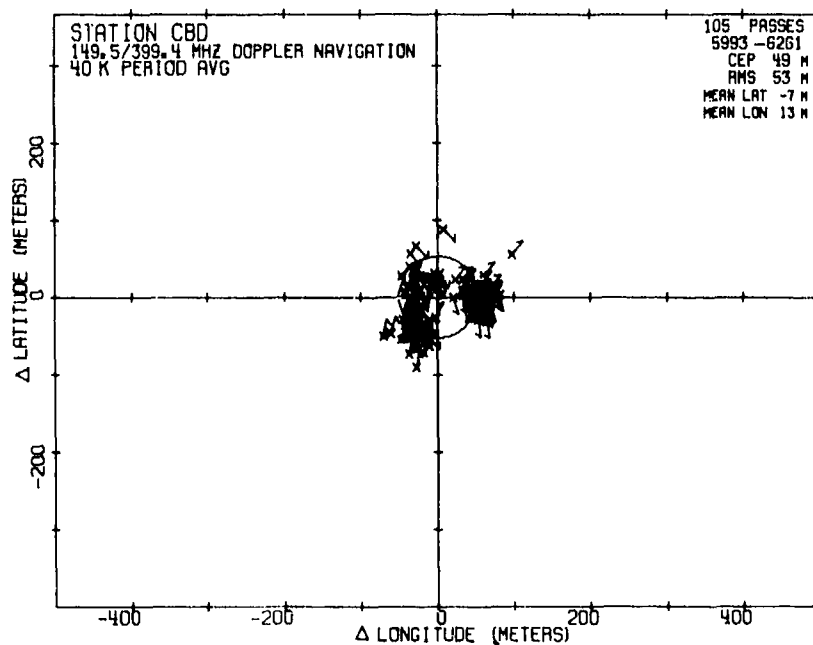
(U) Fig. 11 — 40K doppler (O — C) versus time from
TCA, data set 4

(C) Fig. 12 — 40K doppler navigations,
data set 4

(U) Fig. 13 — 40K doppler (O — C) versus time from
TCA, data set 5

(C) Fig. 14 — 40K doppler navigations,
data set 5

FREQUENCY DIFFERENCE RESULTS

(U) The doppler-frequency correction number K is a measure of the frequency difference between the satellite and navigator's frequency standards during the satellite pass. For the TIMATION II satellite, a typical pass is above the horizon about 15 minutes. Reference to Fig. 15 shows that a quartz-crystal frequency standard is quite stable for this measurement time. Crystal aging (8) causes the frequency difference to drift slowly. However, the amount of frequency drift in 15 minutes is negligible. The doppler mode of navigation employed treats K as an unknown constant during a satellite pass, but the value of K is not further used. Different modes of navigation, such as described in Ref. 6, use the value of K, which explains the interest in studying the frequency difference.

(U) Figure 16 presents the residual values of K for all 407 passes using the 40K doppler measurements. The residuals were obtained by subtracting reference values of K which are obtained using ranging information and a cesium-beam frequency standard. The cesium-beam frequency standard is also used to provide the 5-MHz frequency source for the doppler equipment (Fig. 2). The reference frequency from ranging information is obtained using satellite passes approximately one day apart; hence the accuracy and stability are much better than that obtained using doppler measurements for 15 minutes. Reference to Fig. 16 shows that a small bias in K of -2.8×10^{-10} was present. Figure 17 presents the results for the best equipment conditions and yields a value of $(-2.6 \pm 1.9) \times 10^{-10}$. The bias of -2.6×10^{-10} is statistically significant and indicates that either the equipment or the model used is responsible for this bias. The RMS value of K of $\pm 1.9 \times 10^{-10}$ is directly related to the frequency-measurement noise by a factor which is determined by the satellite-pass geometry.

IONOSPHERIC REFRACTION MEASUREMENTS

(U) The first-order doppler shift is measured through the use of the two coherent frequencies transmitted at 149.5 and 399.4 MHz. Let $f_1 = 399.4$ MHz, $f_2 = 149.5$ MHz, and $k = f_2/f_1$. Then the doppler refraction due to transmission through the ionosphere can be developed (9) in a series given by Eq. (1) and Eq. (2).

$$f_D(f_1) = -\frac{f_1 \dot{R}}{c} + \frac{a_1}{f_1} + \text{ higher order terms} \tag{1}$$

$$f_D(f_2) = -\frac{f_2 \dot{R}}{c} + \frac{a_1}{f_2} + \text{ higher order terms} \tag{2}$$

In Eqs. (1) and (2), the expression $\dot{R}$ is the range rate, c is the speed of light, $-f_1 \dot{R}/c$ and $-f_2 \dot{R}/c$ are the doppler shifts at transmitted frequencies f_1 and f_2, with the ionospheric refraction effect removed, $f_D(f_1)$ and $f_D(f_2)$ are the measured doppler shift at f_1 and f_2, a_1 is the first-order coefficient, and the higher order terms are neglected in this development. Equation (3) is obtained from Eqs. (1) and (2) to solve for the doppler shift at frequency f_1 with the first-order contribution removed.

$$\frac{-f_1 \dot{R}}{c} = [f_D(f_1) - kf_D(f_2)]/(1 - k^2). \tag{3}$$

Now Eqs. (1) and (2) may be used to solve for the first-order contribution of frequencies f_1 and f_2, which is denoted by $\Delta f_D(f_1)$ and $\Delta f_D(f_2)$.

$$\Delta f_D(f_1) = f_D(f_1) - \left(-\frac{f_1 \dot{R}}{c}\right) = \frac{a_1}{f_1} \tag{4}$$

$$\Delta f_D(f_2) = f_D(f_2) - \left(\frac{f_2 \dot{R}}{c}\right) = \frac{a_1}{f_2} \tag{5}$$

$$\Delta f_D(f_1) = (f_2/f_1) \, \Delta f_D(f_2) \tag{6}$$

(U) Equation (6), obtained by combining Eqs. (4) and (5), shows the relationship between the refraction for frequencies f_1 and f_2. For 149.5 and 399.4 MHz, this ratio is near 3/8. The use of Eq. (6) eliminates the need to study the refraction characteristics at each frequency.

(U) The measured first-order ionospheric refraction for a single satellite pass is given in Fig. 18, where the refraction correction is plotted as a function of time from the time of closest approach (TCA) of the satellite. Figure 19 gives a composite of 407 satellite passes and shows the size and shape of the refraction under varying conditions. From Fig. 19 it is seen that for this data span the maximum value of the refraction was about 1 Hz at 399.4 MHz, or 2.5×10^{-9} in terms of fractional frequency deviation. At the point of TCA, the average correction is zero, with an RMS frequency noise level of $\pm 2 \times 10^{-10}$. Reference 10 gives an expression for the first-order refraction which shows that it is directly proportional to the rate of change of total electron content along the
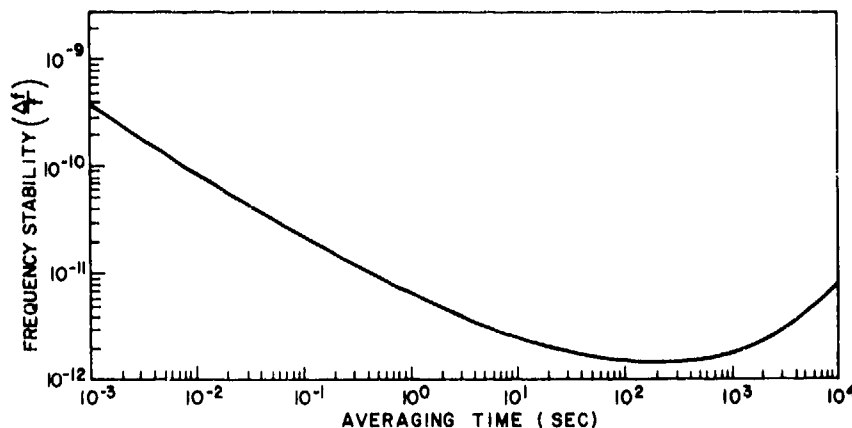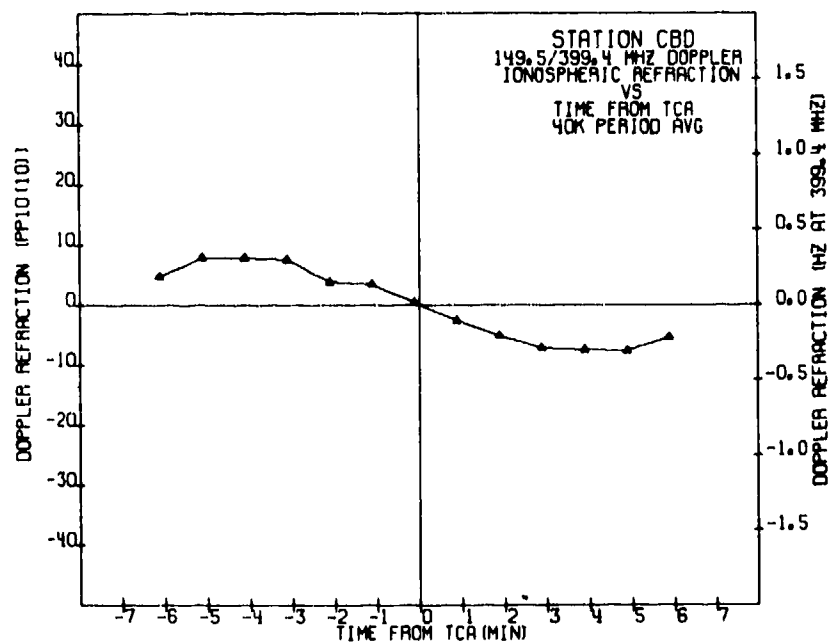

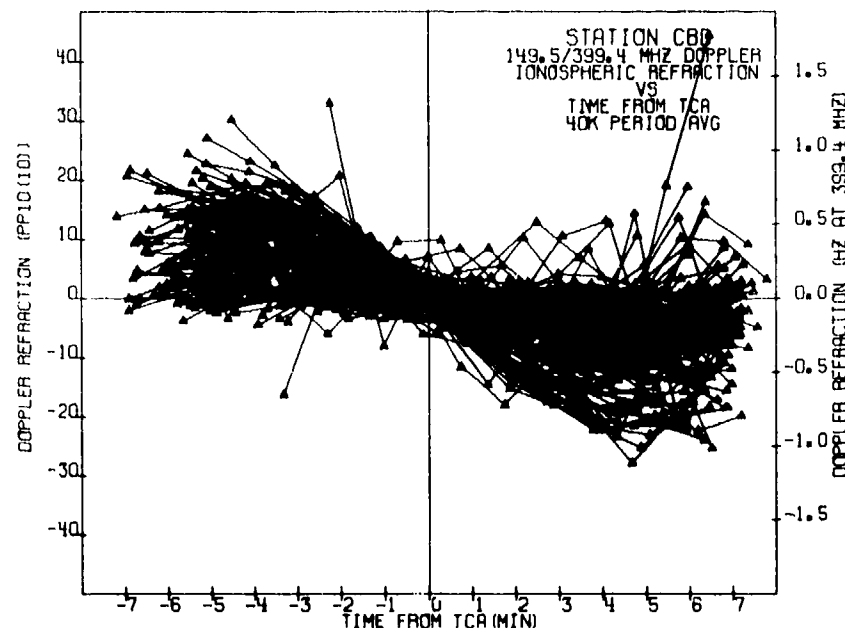(U) Fig. 15 — Frequency stability versus averaging time

(U) Fig. 16 — 40K frequency corrections versus time, 407 passes, data set 6
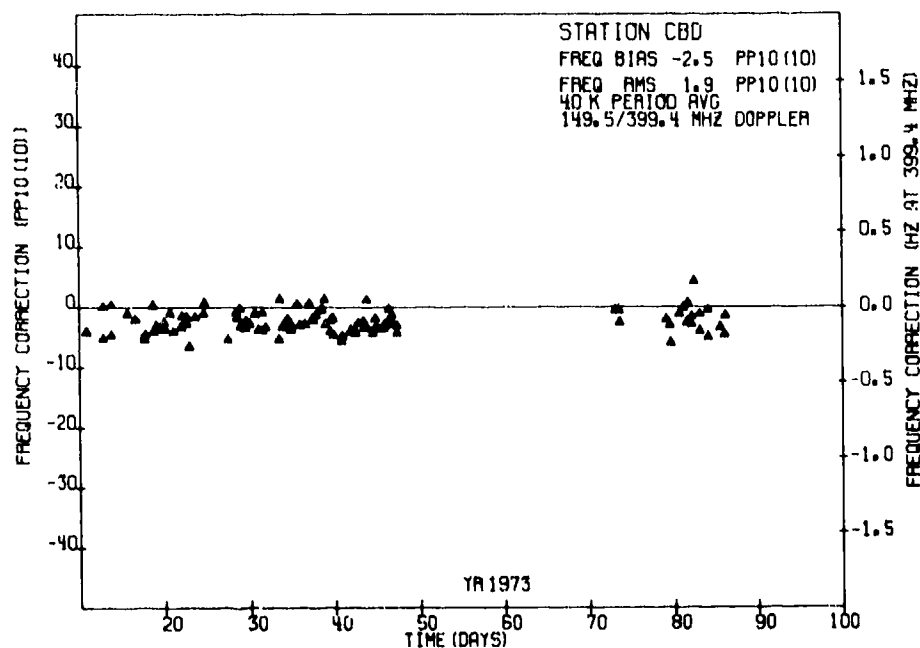
(U) Fig. 17 — 40K frequency correction versus time,
data set 5

(U) Fig. 18 — Doppler refraction connection at 399.4 MHz

(U) Fig. 19 — Composite doppler refraction for 407 satellite
passes at 399.4 MHz

ray path. This reference further shows that the first-order refraction curve can have three
zeros, one near TCA, and the other two can occur near the horizon at the beginning and
end of the pass. The shift of the zero crossing at TCA can be explained by horizontal
gradients in the ionosphere.

(U) The ionospheric refraction, if uncorrected, can introduce an error of several hundred
meters into the navigation fixes and can bias the frequency difference.

ANALYSIS OF RESULTS

(U) The accuracy of the navigation fixes and the frequency-difference results are
summarized in Table 3. Reference to Table 3 shows a strong dependence of navigation
accuracy on doppler data type (1K, 10K, or 40K). Figure 20 presents the RMS frequency
noise versus measurement time for the three data types used, as summarized in Table 4.
This RMS frequency noise figure is calculated using the final navigated position. This
noise figure is a measure of the total system noise and reflects noise contributions from
several sources. However, the predominant effect in Fig. 20 is a linear increase in noise
for short measurement times. Figure 20 also displays the frequency resolution for each
data type. It is apparent from Fig. 20 that measurement times on the order of one
second or more are desirable. For measurement times in excess of a few seconds, a linear
function does not approximate the doppler curve, which introduces errors into the
mathematical model.

(U) Table 3
Frequency Measurement Noise and Resolution

| Doppler Data Type	Time Interval Resolution (microsec)	Nominal Frequency Resolution (Hz)	RMS Frequency Noise	Frequency Truncation Error Range (Hz)	
1K	0.1	0.04	20.9×10^{-10}	−0.08163	−0.01384
10K	0.1	0.004	2.7×10^{-10}	−0.008163	−0.001384
40K	0.1	0.001	1.5×10^{-10}	−0.002777	−0.000391

(C) Table 4
Summary of Measurement Noise, Navigation Accuracy, and Frequency
Difference for Three Data Types

Data Set Number	Doppler Data Type	RMS Measurement Noise ($\times 10^{-10}$)	RMS Navigations (m)	Average		Frequency Difference	
				Latitude (m)	Longitude (m)	Bias ($\times 10^{-10}$)	RMS ($\times 10^{-10}$)
1	1K	20.9	240	−25	13	0.4	17.1
2	10K	2.7	58	−11	7	−1.1	3.5
5	40K	1.5	53	−8	−13	−2.6	1.9

(U) The RMS frequency noise measurements in Table 3 do not completely account for the navigational-accuracy results. The relationship between random measurement errors and navigational accuracies may be estimated through the use of a GDOP factor. The GDOP factor is used to estimate errors caused by the relative location of the satellite and the navigator's platform. In this report we will denote the two-dimensional GDOP factor by the term PDOP (Position Dilution Of Precision). Figure 21 presents a plot of the PDOP versus maximum elevation angle and shows that the minimum PDOP is reached at a maximum elevation angle of 44 degrees. The PDOP factor is calculated using the square root of the trace of the submatrix involving the navigator's position from the least-squares inverse matrix. The units on the PDOP factor are in meters per part in 10^{-10} (m/10^{-10}), which gives the relationship between position errors and frequency stability. The PDOP factor does not depend on the frequency used to obtain the doppler measurements. Reference to Fig. 21 shows a sharp increase in the PDOP factor for elevation angles less than 15 degrees or greater than 70 degrees. For maximum elevation angles above 70 degrees, the solution for the component of the navigator's position that lies across the track of the satellite becomes diluted; for maximum elevation angles below 15 degrees, the total time the satellite is above the horizon decreases, the signal strength decreases, and second-order
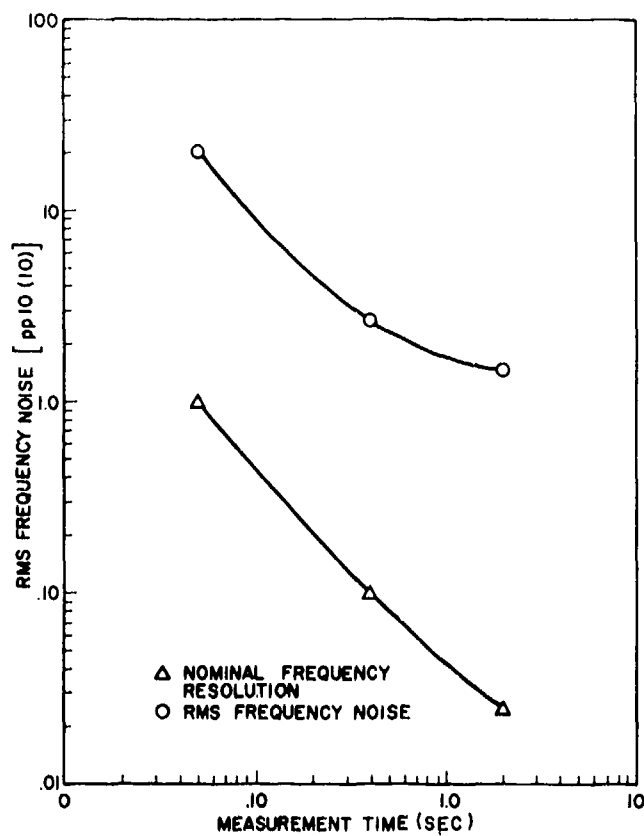
(U) Fig. 20 — RMS frequency noise
versus measurement time
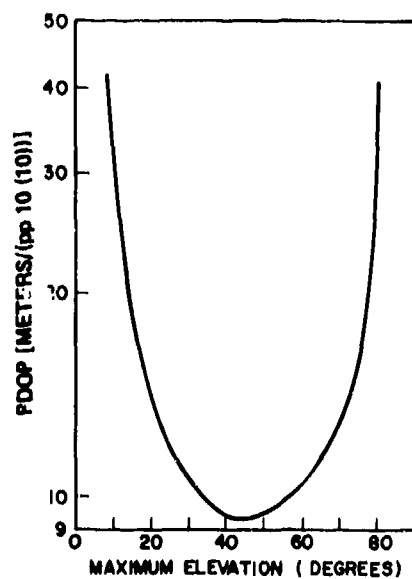
(U) Fig. 21 — Two-dimensional GDOP versus
maximum elevation angle

ionospheric errors and tropospheric-refraction errors increase. For these reasons, satellite passes below 15 degrees and above 70 degrees are excluded. The average value of the PDOP factor for satellite passes between the range from 15 to 70 degrees is $14m/10^{-10}$ for the passes used in this report.

(C) To fully realize the advantages of dual-frequency doppler navigations, the single-frequency-navigation case must also be examined. The 150-MHz-only case is shown in Fig. 22, and the 400-MHz case is shown in Fig. 23. Comparison of these two cases reveals that the 400-MHz-only data have much more accurate navigation fixes than the 150-MHz-only data; the 400-MHz data have an RMS value of 84 m, whereas the 150-MHz data have an RMS of 739 m. This result corresponds to an RMS value of 53 m for the dual-frequency navigations, as was discussed previously, in "Doppler Navigation Results." This large difference in navigational accuracy is due primarily to the ionospheric-refraction effects on the transmitted signals and shows the importance of doing dual-frequency navigations.
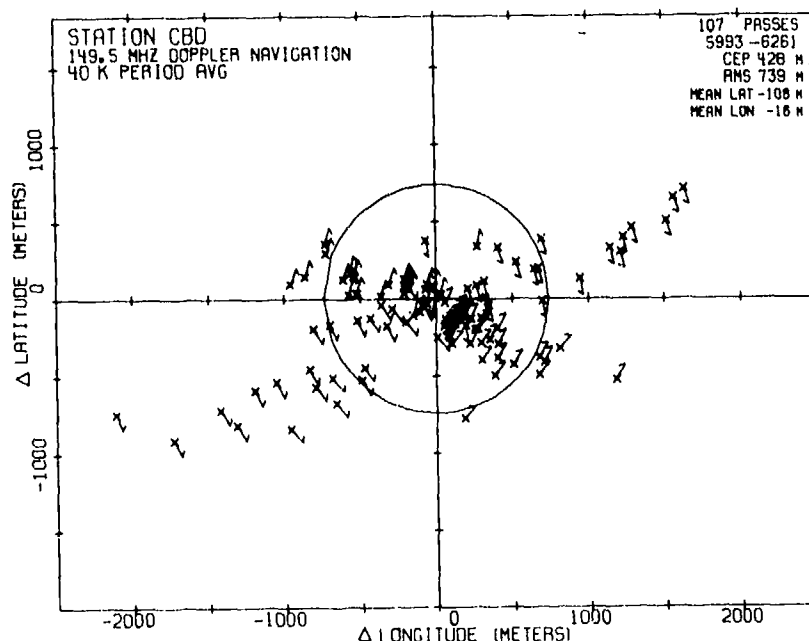

(C) Fig. 22 — 150 MHz only 40K doppler navigations
data set 5

(U) Another situation studied resulted from the navigator making an error in assuming his height. The data used to determine this effect were dual-frequency doppler with a 1000-m height adjustment in the coordinates of the CBD receiving station. The results of this case are contained in Fig. 24. The resulting RMS value is 1369 m, which yields approximately a 1.4-m navigation error per meter height error. The navigation error introduced is in a direction across the track of the satellite and also is dependent on the maximum elevation of the pass.
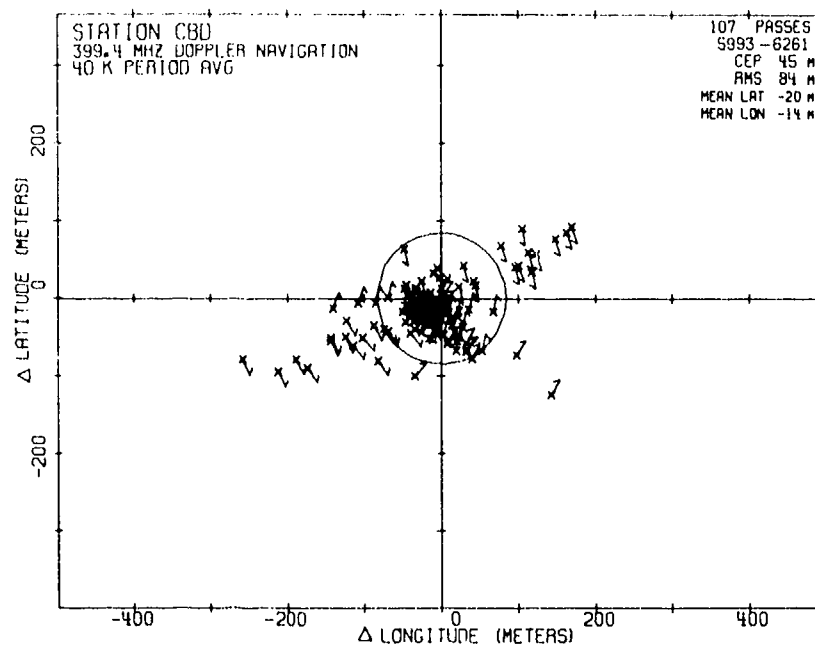
(C) Fig. 23 — 400 MHz only 40K doppler navigations
data set 5
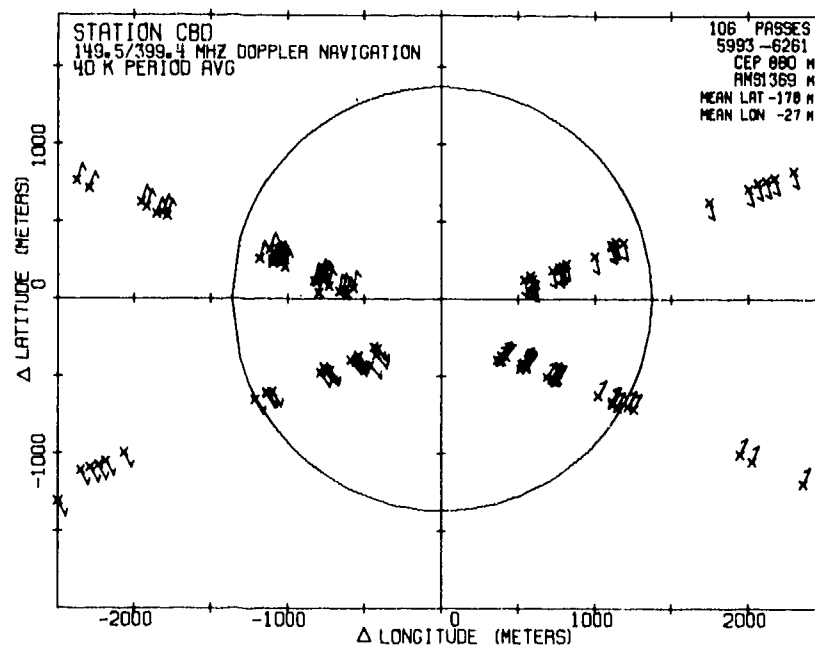
(U) Fig. 24 — 1000 meter height error doppler navigations
data set 5

CONCLUSIONS

(C) When single-frequency TIMATION navigation fixes are performed, a strong influence
is exhibited by the ionosphere, the degree of which is dependent on the carrier frequency.
The RMS of the dual-frequency navigation accuracy is 53 m, whereas for the 400-MHz
transmitter alone the accuracy is 84 m, and for the 150-MHz transmitter alone the
accuracy is 739 m.

(U) The two-dimensional PDOP factor, which relates the relative position of the satellite
with respect to the navigator, is independent of the carrier frequency employed. The
average value of PDOP for passes with maximum elevation angles between 15 and 70
degrees is 14 $m/10^{-10}$, with PDOP being directly related to the fractional frequency
stability of the doppler measurements.

(U) The RMS measurement noise, obtained from the least-squares solution, is dependent
on the length of the measurement time and equipment. For a 0.050-sec average measure-
ment time (1K doppler), the noise is 20.9×10^{-10}, whereas for a 0.50-sec average measure-
ment time (10K doppler), the value is 2.7×10^{-10}, and for a 2.0-sec average measurement
time (40K doppler), the noise is 1.5×10^{-10}.

(U) An error in the user's assumed height causes approximately a 1.4-m navigation error
per meter in the position solution.

(U) The frequency difference can be determined to a precision of $\pm 1.9 \times 10^{-10}$ using
the doppler data collected from a single satellite pass. A small bias of -2.8×10^{-10} was
detected and believed to be an equipment-related error.

ACKNOWLEDGMENTS

(U) The authors acknowledge the guidance of Mr. D. W. Lynch, Head of the Advanced
Techniques and Systems Analysis Section. Much credit is also due to the Bendix Field
Engineering personnel who maintained the CBD field station. The authors further
acknowledge the technical support of Mr. Robert Hill, NWL, and Mr. James Buisson, NRL.

REFERENCES

1. Easton, R.L., "The Role of Time/Frequency in Navy Navigation Satellites," Proc. IEEE,
    May 1972, pp. 530-539.

2. Easton, R.L., "Optimum Altitudes for Passive Ranging Satellite Navigation Systems,"
    Naval Research Reviews, pp. 8-17, Aug. 1970.

3. McCaskill, T.B., Buisson, J.A., and Lynch, D.W., "Principles and Techniques of Satellite
    Navigation Using the Timation II Satellite," NRL Report 7252, June 17, 1971.

4. Buisson, J.A. and McCaskill, T.B., "Timation Navigation Satellite System Constellation
    Study," NRL Report 7389, June 27, 1972.

CONFIDENTIAL

5. Buisson, J.A., McCaskill, T.B., and Thompson, J.E., "Range Navigation Results using the Timation II Satellite," NRL Report 7511 (Confidential Report, Unclassified Title), Feb. 12, 1973.

6. Easton, R.L., Buisson, J.A., and McCaskill, T.B., "Instantaneous Position Fixing Results Obtained by Measuring Satellite Range and Doppler," NRL Repc ⸱ 7580 (Confidential Report, Unclassified Title), 1973.

7. Buisson, J.A., Lynch, D.W., and McCaskill, T.B., "Time Transfer Using the Timation II Satellite," NRL Report 7559 (Confidential Report, Unclassified Title), July 4, 1973.

8. Bartholomew, C.A., "Quartz Crystal Oscillator Development for TIMATION," NRL Report 7478, Oct. 25, 1972.

9. Newton, R.R., "The Navy Navigation Satellite System," Space Research VII, North-Holland Publishing Company, Amsterdam.

10. Willman, J.F. and Tucker, A.J., "Accuracy of Satellite Doppler Data for Ionospheric Study, Navigation and Geodesy," J. Geophys. Res., Space Physics, Vol. 73, No. 1, pp. 385-392.

DOCUMENT CONTROL DATA - R & D

(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)

1. ORIGINATING ACTIVITY *(Corporate author)*	2a. REPORT SECURITY CLASSIFICATION
Naval Research Laboratory Washington, D.C. 20375	CONFIDENTIAL
	2b. GROUP XGDS-3-1988

3. REPORT TITLE

DOPPLER ONLY NAVIGATION USING THE TIMATION II SATELLITE (Unclassified Title)

4. DESCRIPTIVE NOTES *(Type of report and inclusive dates)*

This is an interim report on a continuing problem.

5. AUTHOR(S) *(First name, middle initial, last name)*

Thomas B. McCaskill, Charles W. Arvey, and Hugh B. Gardner

6. REPORT DATE	7a. TOTAL NO. OF PAGES	7b. NO. OF REFS
December 3, 1973	28	10

8a. CONTRACT OR GRANT NO. NRL Problem R04-16 b. PROJECT NO. PM-16-211/058C/3W34110000 c. d.	9a. ORIGINATOR'S REPORT NUMBER(S) NRL Report 7657 9b. OTHER REPORT NO(S) *(Any other numbers that may be assigned this report)*

10. DISTRIBUTION STATEMENT

Distribution limited to U.S. Government agencies only; test and evaluation; December 1973. Other requests for this document must be referred to the Director, Naval Research Laboratory, Washington, D.C. 20375

11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY Department of the Navy Naval Space Project Office (PME-106) Washington, D.C.

13. ABSTRACT (Confidential)

(U) The TIMATION II satellite is an experimental model which is part of a range and doppler measurement satellite system proposed by NRL as the Navy's candidate for the Department of Defense Navigation Satellite System (DNSS). The TIMATION project has been conducted at NRL under the sponsorship of the Navy Space Project Office (PME-106) and the Naval Air Systems Command. A doppler mathematical model has been devised which permits ready analysis of the doppler data collected at the CBD field station over a 1-1/2-year time period.

(C) The studies performed have shown that the best navigational accuracies, having an RMS of 53 meters (174 feet), are achieved by using dual-frequency doppler measurements. The 400-MHz single-frequency data give the next best accuracy, with an RMS of 84 meters (276 feet), and are followed by the 150-MHz single-frequency data, which yield an accuracy of 739 meters (2424 feet) RMS. The data collected are three types: 1K, 10K, and 40K doppler count. By varying the count interval, the effect of measurement time on navigational accuracy can be observed.

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
TIMATION						
Satellite navigation						
Range and/or doppler						
Passive measurements						
Least squares solution						
Ionospheric refraction						
Frequency difference						

2640

UNCLASSIFIED

CONFIDENTIAL

NRL Report 7657

Cy 7

DOPPLER Only Navigation Using the Timation II Satellite
[Unclassified Title]

T. B. McCASKILL, C. W. ARVEY,
AND H. B. GARDNER

Space Metrology Branch
Space Systems Division

AD 528266

December 3, 1973

NAVAL RESEARCH LABORATORY
Washington, D.C.